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Research review paper

Innovation in biological production and upgrading of methane and hydrogen for use as gaseous transport biofuel

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ABSTRACT

Biofuels derived from biomass will play a major role in future renewable energy supplies in transport. Gaseous biofuels have superior energy balances, offer greater greenhouse gas emission reductions and produce lower pollutant emissions than liquid biofuels. Biogas derived through fermentation of wet organic substrates will play a major role in future transport systems. Biogas (which is composed of approximately 60% methane/hydrogen and 40% carbon dioxide) requires an upgrading process to reduce the carbon dioxide content to less than 3% before it is used as compressed gas in transport. This paper reviews recent developments in fermentative biogas production and upgrading as a transport fuel. Third generation gaseous biofuels may be generated using marine-based algae via two-stage fermentation, cogenerating hydrogen and methane. Alternative biological upgrading techniques, such as biological methanation and microalgal biogas upgrading, have the potential to simultaneously upgrade biogas, increase gaseous biofuel yield and reduce carbon dioxide emission.
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Contents

Abbreviations: AD, anaerobic digestion; AFB, anaerobic fermentative bacteria; FAN, free ammonia nitrogen; HPB, hydrogen-producing bacteria; GHG, greenhouse gas; HRT, hydraulic retention time; LCFA, long chain fatty acid; LHV, lower heating value; MC, methane content; NADH, reduced nicotinamide adenine dinucleotide; NGV, natural gas vehicle; NTP, normal temperature and pressure; OFMSW, organic fraction of municipal solid waste; OLR, organic loading rate; OMEGA, offshore membrane enclosures for growing algae; P2G, power to gas; PSA, pressure swing adsorption; SAY, specific ammonia yield; SMP, soluble metabolic product; SMY, specific methane yield; TAN, total ammonia nitrogen; TS, total solids; VFA, volatile fatty acid.

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1. Introduction

1.1. Energy and transport fuel

Global primary energy consumption in 2013 has reached 535 EJ (or 12,730 Mtoe equivalent); this is an increase of 28% when compared with 2003, almost double the figure compared with 1978. Fossil fuels were still the dominant energy source in 2013, accounting for 87% of total primary consumption (BP, 2014). Greenhouse gas (GHG) emissions from fossil fuel utilisation have resulted in serious environmental problems, such as climate change, rise in sea level and biodiversity loss (Nigam and Singh, 2011).

On a global scale, the conversion ratio from primary energy to final energy is 1.49 (IEA, 2014). About one-third of final energy consumption is associated with transport, the resources of which are dominated by liquid fuels (i.e., petrol and diesel) (IEA, 2014; Murphy et al., 2013). Gaseous fuels play an increasingly important role nowadays: in excess of 17 million natural gas vehicles (NGVs) exist, with an annual energy consumption of 2.7 EJ (or 63.5 Mtoe equivalent), predominately in developing countries, such as Argentina, Brazil, China, India, Iran and Pakistan (NGVA Europe, 2013).

1.2. Role of biofuels

The European Union (EU) Renewable Energy Directive states that 10% of energy in transport should be renewable by 2020 (European Union, 2009). Biofuels, which are predominantly produced from biomass, may play a major role for renewable energy supply in transport (Allen et al., 2014; Nigam and Singh, 2011).

Biofuels, such as biogas, biomethanol, bioethanol and biodiesel, are considered an alternative to fossil fuels in the future because they can reduce transport emissions and increase the security of supply (Nigam and Singh, 2011). In 2008, biofuels provided about 21% of road transport fuels in Brazil, 4% of road transport fuels in the United States, and 3% of road transport fuels in the EU. The International Energy Agency (IEA) suggested that biofuels can provide 27% of global transport fuel (equal to 32 EJ) by 2050; meanwhile, the global bioenergy potential of "low-risk" biomass feedstocks may reach 475 EJ (IEA, 2011).

1.2.1. Generations of biofuels

Biofuels may be classified into three different generations, depending on biomass feedstock (see Table 1). The first generation biofuels can also be called conventional biofuels, and they are mainly obtained from food crops and edible oil seeds; their technologies are mature and relatively inexpensive (Kiran et al., 2014a; Nigam and Singh, 2011). However, first generation biofuels draw wide criticism because of their competition with food and fibre production, as well as large consumption of fertiliser and fresh water. Excess production of first generation biofuels will significantly increase food prices (Kiran et al., 2014a).

Second generation biofuels are mainly produced from lignocellulosic biomass, non-edible oil seeds and waste streams (Nigam and Singh, 2011). They have the advantages of having less food crop competition. In many developing countries, waste lignocellulosic residues such as straws are traditionally burned in the fields, which may result in serious air pollution. Conversion of waste lignocellulosic residues to biofuels via clean technologies would be beneficial for the environment. Lignocellulosic biomass may need energy-intensive pre-treatments prior to the first generation biofuel production stage (Zheng et al., 2014). Therefore, the energy requirements for second generation biofuels can be higher than those for first generation biofuels. Meanwhile, the energy cost in the production of substrates in second generation processes may be low compared with food crops (e.g., costs in ploughing, fertilising and harvesting). Second generation biofuels may be cheaper than first generation biofuels, if the capital costs and more complex pre-treatment processes can be offset by the cheap substrate resources. However, second generation biofuels may not be commercially available by 2020, either because of their techniques or costs (Murphy et al., 2015).

Third generation biofuels are mainly derived from algae (Dutta et al., 2014). Algae, which can be classified as microalgae and macroalgae (seaweeds), are known for high photosynthesis efficiencies and productivities, thereby resulting in lower area requirements compared with land-based plants, such as maize, corn and switch grass (Demirbas, 2010; Dismukes et al., 2008; Wei et al., 2013; Xia et al., 2015c). Algae can be cultivated in non-freshwater sources, such as salt water and seawater on non-arable land, and do not compete with common food resources (Jones and Mayfieldt, 2012). Furthermore, algal cultivation combining wastewater and flue gas treatment shows significant

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